Combining offshore and onshore renewables with energy storage and diesel generators in a stand-alone Hybrid Energy System

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Abstract

Most settlements in remote and isolated locations rely on imported diesel to provide electricity and thus electricity prices are usually very high. Hybrid Energy Systems (HES) which combine renewable electricity generation with energy storage and backup diesel generators have the potential to replace the majority of fossil fuel based electricity with renewable electricity while also reducing the price for the residents. However, due to the variability of the renewable electricity generation either a much larger renewable generation capacity or a very large battery capacity would be required to remove the diesel generators completely. By combining electricity generation from different renewable resources the fraction of power generated by fossil fuels can be reduced. While most HES system consider only wind turbines and solar PV panels, many island have a very good wave resource which could be exploited. In this contribution a mathematical framework is used to investigate the effect of combining wind turbines and wave energy converters (WEC) on the required amount of backup diesel generation and electricity storage as well as on the renewables fraction. Most waves are wind generated and there is usually a time delay of several hours between the wind and wave energy resource. Thus the waves act as an energy store for the wind and the integration of WECs in a HES can reduce the required amount of backup diesel generation and energy storage in comparison to a wind only HES. While WECs are less developed and currently more expensive compared to wind turbines, they offer enticing prospects for future HESs in remote coastal locations.

1 Introduction

Currently many remote locations such as islands are not connected to the main electricity network and instead have an isolated microgrid which relies on diesel generators to provide the required electricity. This results in the dependency on imported and often expensive fossil fuels and the resulting problems: high electricity prices, emission of greenhouse gases and other pollutants. On the other hand, many of these remote locations have excellent renewable resources which could provide enough electricity to fulfil the demand. With the recent cost-reductions in renewable electricity generation this option is becoming more and more competitive with conventional diesel generators. On top of this, the electricity would be non-polluting and independent on fuel imports. However, renewable electricity generation such as solar, wind and wave is variable and more importantly non-dispatchable. Thus a stand-alone renewable generator would either be unable to fulfil the electricity demand at all times, e.g. solar has periods of no power output, or would need to be massively oversized, e.g. wind turbines (WT) and wave energy converters (WEC).

A potential solution to this problem is the combination of multiple, different electricity generators in a so called Hybrid Energy System (HES). Usually a HES contains one or more different renewable generators plus diesel generators and often also a battery bank. The diesel generator is dispatchable and acts as a backup to balance the mismatch between electricity demand and renewable electricity supply. While the initial costs for the diesel generator are much lower than for renewable generation, the operating and maintenance costs are much higher due to the fuel requirements. By integrating also a battery bank the total renewable energy fraction, i.e. fraction of the total energy demand covered from renewable generators, can be increased and thus the fuel consumption decreased. This reduced fuel consumption is achieved by storing electricity at times when the renewable supply is larger than the demand; this electricity would otherwise be wasted. While a battery bank can reduce the time mismatch, a very large battery would be required to run the microgrid entirely with a single form of renewable generation (without diesel backup). By integrating different forms of renewable generation the fluctuations in electricity generated and in particular the length of times with very low production are reduced. This allows the reduction in the battery capacity while keeping the renewable energy fraction constant.

The interest in HES for microgrids started in the late 1970s and has experienced a large growth in recent years. The main challenges are the sizing and economics of the system followed by the control of the various units [1]. The sizing of the HES components is crucial to ensure a reliable supply at the lowest possible cost. However, these two main objectives are usually conflicting and thus for each system a compromise which depends on the requirements needs to be found. The design and sizing of a HES depends on a large number of design parameters: system parameters and costs for each generator and battery; demand profiles; renewable resource profiles. In one of the first publications about HES, Andrews [2] used a Monte Carlo simulation to investigate the effect of varying proportions of wind and solar on the required energy storage capacity to fulfil the annual demand. It was realised early on by Castle et al. [3] that the design of an efficient and cost-competitive HES is challenging and requires the use of a numeric optimisation. The authors developed a computational tool for the automatic sizing of wind/photovoltaic (PV)/diesel/battery HES. They concluded that the combination of different renewables reduces the required battery capacity and that a system which requires only a 95% renewable percentage, i.e. 5% of load supplied by a diesel generator, requires a much smaller battery capacity compared to a system with a 100% renewable percentage. In recent years a large number of studies have investigated the optimal sizing of HES [4]–[6] while less research into the control of the various components has been reported [7].

While most HES provide the electricity demand and use only wind and solar, the concept was early on applied to different demand types, e.g. medium-temperature heat for cooking and heating and mechanical shaft power, and for a range of renewable resources, e.g. biogas and small-scale hydro [8]. Most HES consider battery storage but the integration of pumped hydro storage [9] and hydrogen [10] (which is currently not cost competitive) are gaining attention. While the combination of wind and solar in HES is widespread and well developed, the integration of other renewable resources, such as hydro, biomass or municipal waste, is at an early stage in the development. Particularly, the integration of Ocean Renewable Energy into HES is in its infancy. However, the integration of offshore wind and WECs is gaining more attention and is offering a large list of synergies [11], e.g. common grid and foundation infrastructure, shared logistics and smoother power output. The last point is also true for the integration of WECs into a wind only HES. An overview of the different WEC concepts and technologies is given in [12].

Many of the Greek island are not connected to the mainland electricity grid and are dependent on oil fired electricity generation. In the last years the Greek government has proposed plans to develop HES on the Greek island to achieve greater energy autonomy [13]. Several studies have investigated the integration of wind and solar electricity generation with different storage solutions in the Greek islands [9], [13]. A recent study has designed a hybrid renewable generation system combining wind turbines with a WEC highlighting the potential and opportunities for such a system [14]. This study uses the JonSwap wave model and estimates the general performance of the system with a daily resolution. The results encourage the further evaluation of the concept with a more sophisticated wave model, a higher temporal resolution and the integration with energy storage systems.

In this contribution a detailed design and optimisation of a HES which includes wind turbines and WECs is presented. This HES combining wind and wave electricity generation achieves a higher renewable fraction compared to a wind only HES.

2 HES modelling and optimisation framework

A schematic of the HES considered in this contribution is shown in Figure 1. The main components of the HES are the wind turbines, WECs, batteries and diesel generator. The renewable electricity generators are connected to a DC bus. From this DC bus the AC load is supplied through a DC/AC converter. A simple control scheme controls the charging and discharging of the batteries and the operation of the diesel generators. Briefly, if the renewable electricity generation is larger than the load the batteries are charged with the remaining energy. If there is a shortage of energy this is supplied by discharging the batteries if these have a sufficiently high state of charge. If the batteries can't fulfil this load diesel generators are switched on. In this case the remaining load is first fulfilled by the diesel generators which are running at their nominal power rating and the remainder is provided by the battery.

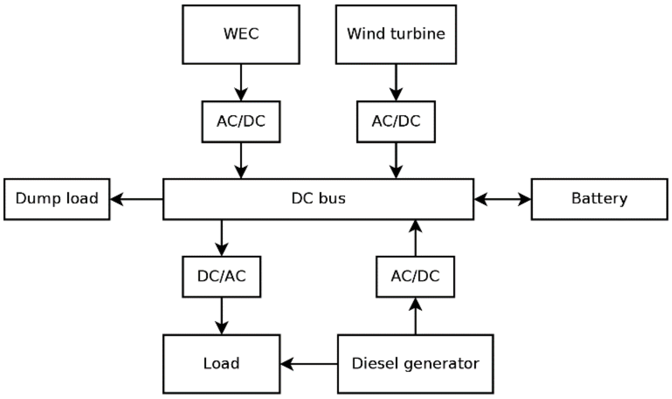

Figure 1: Schematic of the proposed HES.

The individual components of the HES can be modelled with different approaches and different levels of accuracy. For example, Bajpai and Dash [15] review equivalent circuit models for HES components while Deshmukh and Deshmukh [1] give an overview of parameterised models giving the power flows of HES components. The more complex models which might be closer to the actual component performance require a larger number of parameters to achieve this higher accuracy. Since this contribution is mainly interested in showing the relative benefits of including WEC in HES the parameterised models from [1] offer a good balance between complexity and accuracy.

2.1 Wind turbine model

The performance of the wind turbine depends on the wind speed at hub height and on the design of the wind turbine [1]. The wind speed at hub height can be calculated from the following power law

$$v_T = v_m \left(\frac{h_T}{h_m}\right)^{0.13}$$

where v and h are the wind speed and the hub height and the subscripts m and T indicate the measured values and the wind turbine, respectively. The power output of the wind turbine can be calculated from the power curve which is given by

$$P = \begin{cases} 0 & , v < v_{ci} \\ aP_r(v^3 - v_{ci}^3) & , v_{ci} < v < v_r \\ P_r & , v_r < v < v_{co} \\ 0 & v > v_{co} \end{cases}$$

here P_r is the rated power and v_{ci}, v_r and v_{co} are the cut-in, rated and cut-out wind speeds at hub height, respectively. The parameter a is calculated by $a = (v_r^3 - v_{ci}^3)^{-1}$. The power the wind turbine provides to the grid is given by $P_{wind} = \eta P$ where η is the efficiency of the inverter.

2.2 Wave energy converter model

The wave power per unit length of wave crest can be calculated from the formula $P = \frac{\rho g^2}{64\pi} H_{sig}^2 T_e$ where ρ is the fluid density, g the acceleration by gravity, H_{sig} the significant wave height and T_e the wave energy period. From this formula it is obvious that the combination of wave height and energy period determines the sea state and the energy content of waves.

While different WECs operate on different principles [12] the wave energy conversion can be described through a power matrix. The power matrix links the wave height and wave energy period to the power output. This power matrix has cut in and cut out wave heights and energy periods. The power matrix can be calculated numerically [16] or taken from experimental data. In this study the bottom-fixed heave-buoy array Wavestar 600kW WEC is used [17]. This WEC has a relatively low cut-in wave height and wave energy period and is thus suitable for the Mediterranean. The power matrix from [17] is shown in Figure 2 and the values between the given points are calculated by linear interpolation. The power to the grid of the WEC is $P_{wave} = \eta P$.

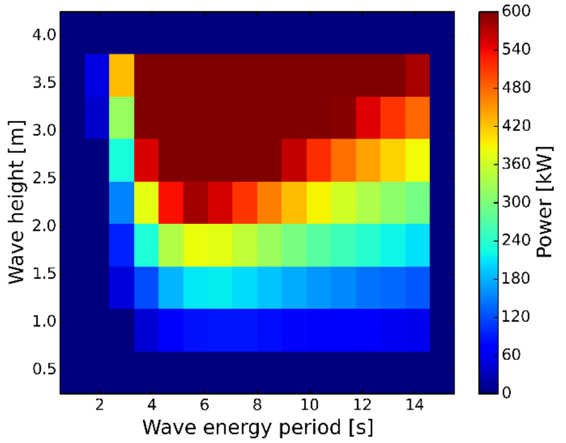

Figure 2: Wavestar power matrix.

2.3 Battery model

The battery can be described with models of varying complexity, ranging from models taking the chemistry into account to parameterised models. The parameterised models can be split into state of voltage and state of charge (SoC) models. The former require a significant number of parameters which need to be measured for each battery at different conditions [18]. The SoC model while potentially less accurate depends only on usually available parameters and gives a satisfactory level of detail. In each time step the SoC is modified by taking the self-discharge rate η_s into account and the amount charged/discharged during this time step. The charge/discharge amounts include the charging efficiencies and also depend on the operation of the HES and the limits of the battery, e.g. maximum SoC reached or the battery is empty.

2.4 Diesel generator model

The diesel generators provide the backup power generation when the renewable generation and battery bank can't fulfil the power demand. The power output of diesel generators can be calculated based on the efficiency at a particular load factor, i.e. fuel consumption. Here the diesel generators are always either switched off or run at their rated capacity.

2.5 Optimisation of the HES

The sizing of the different units of the HES is performed through a numerical optimisation routine with the multiple objectives of maximising the renewable fraction while simultaneously minimising the battery capacity and wasted renewable energy, i.e. renewable energy which can't be directly used and needs to be dumped (see Dump load in Figure 1). These objectives are obviously conflicting and thus the sizing will be a compromise between these objectives. In the optimisation the non-renewable fraction is minimised and the wasted renewable energy is expressed as a fraction of the annual energy demand.

During the optimisation the HES simulation is linked to an optimisation routine. The flowchart in Figure 3 gives an overview of this approach.

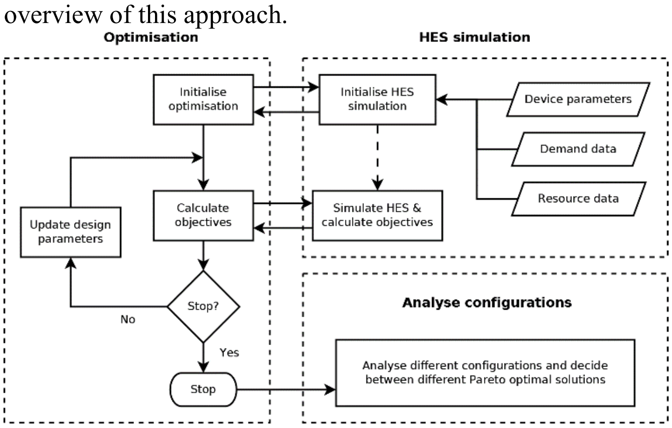

Figure 3: Schematic of the optimisation.

The optimisation routine in this contribution is the multi-objective genetic algorithm NSGA2 from the Python module inspyred [19]. The multi-objective optimisation produces a number of Pareto optimal solutions. These solutions are equivalent in the Pareto sense and present the compromise between the different objectives. In a further step indicated by the 'Analyse configurations' block in Figure 3 one of these solutions needs to be picked. This decision requires the consideration of social, political and other criteria not included in the optimisation. A discussion of this goes beyond this contribution. In a future publication also the control and dispatch of the individual units will be included in the modelling and optimisation of the HES.

3 Electricity demand and renewable resource

The design of the HES requires accurate demand and renewable resource data. Here demand and resource profiles with a temporal resolution of one hour are used.

3.1 Demand data

Astypalaia is located in the Dodecanese Archipelago in the south of the Aegean Sea. The island has about 1300 inhabitants and is isolated from the main Greece electricity grid and currently all electricity is provided by a small fossil fuel power plant. In 2003 the island had a peak demand of 1.78 MW and an annual electricity consumption of 5419 MWh [9]. An average daily demand profile was extracted from [9] and overlaid with the daily variations typical for Greek islands from [13] plus a small random element. The resulting synthetic demand profile shown in Figure 4 matches the peak demand and annual electricity consumption of Astypalaia.

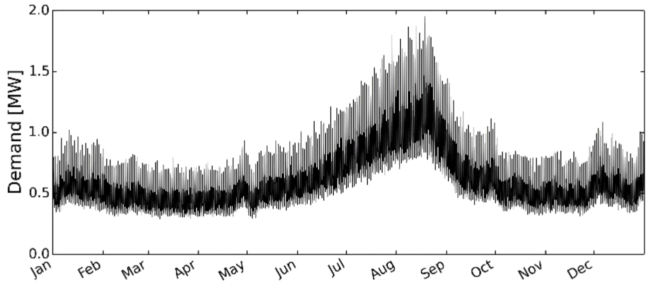

Figure 4: Synthetic electricity demand curve for Astypalaia.

3.2 Wind resource

The wind datasets were provided by NCAR/NCEP and are a result of global wind and precipitation models which have been validated and used in various meteorological applications [20]. The hourly wind speed at 10 metre above sea level is given in Figure 5. The histogram of wind speeds at a hub height of 35 metres in Figure 6 shows that for the majority of the year the wind speed is above 3 m/s. Thus Astypalaia has a wind resource which is favourable for wind turbines.

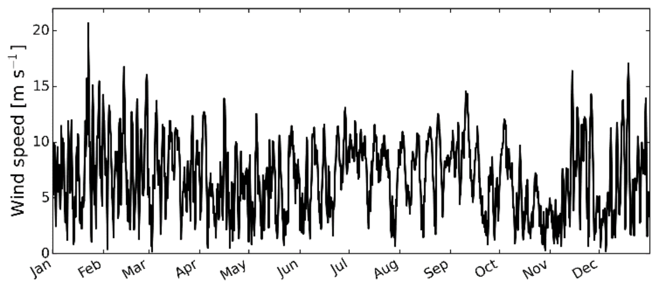

Figure 5: Hourly wind speed at 10 metre above sea level.

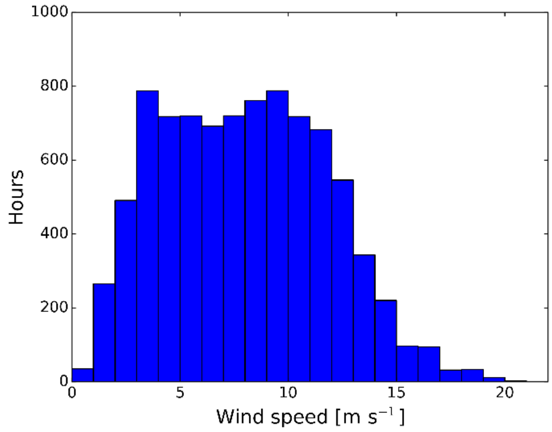

Figure 6: Wind speed histogram at 35 metres hub height.

3.3 Wave resource

The wave energy resource of Astypalaia was calculated with SWAN (www.swan.tudelft.nl/) and is shown in Figure 7.

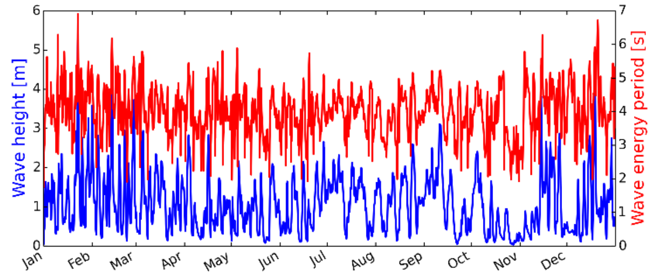

Figure 7: Hourly wave height and wave energy period.

The wave numerical model SWAN is a third generation spectral phase averaged model appropriate for coastal and nearshore locations. The model was nested twice in order to provide high accuracy for the final coastal resource around Astypalaia. The initial mesh covered all the Mediterranean and used to provide spectral information for the subsequent finer resolution run, with resolution of 0.5x0.5 degrees. The finer mesh has a spatial resolution of 0.025x0.025 degrees, while all non-linear and depth to wave interactions were considered and adjusted accordingly [21].

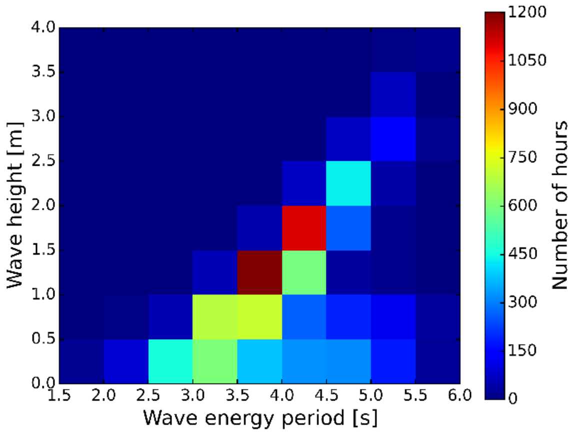

Figure 8: Histogram of the sea state for one year.

For the characterisation of the resource it is useful to evaluate the relative occurrence of different sea states. Figure 8 shows that for a large number of hours the wave resource has a wave height of around 1.5 metres with a wave energy period of around 3.5 seconds.

4 Astypalaia case study

The HES model presented in section 2 is used to investigate the effect of combining wind and wave renewable electricity generation in Astypalaia.

4.1 Specific components of the HES

Astypalaia has an average electricity demand of around 600 kW thus for the design of the HES it makes sense to pick electricity generation units with a rated capacity below 600 kW. The specifics of the diesel generator, wind turbine and WEC are given in the following list:

- Perkins 175 kW diesel generator: hourly diesel consumption at rated capacity is 48 litres
- Vestas V27 wind turbine: hub height 35 m; rated power 225 kW; cut-in, rated and cut-out speed of 3.5, 14 and 25 m/s
- Wavestar 600kW WEC: see section 2.2 for details

It is assumed that all inverters have an efficiency of 95%. Both the charging and discharging efficiency of the battery was assumed to be 95% which gives a relatively high but not unreasonable round-trip efficiency of ~90%.

4.2 Resource assessment

The wind resource histogram in Figure 6 shows that for most hours of the year the wind speed is above the cut-in speed of the Vestas V27 wind turbine. From the sea state histogram in Figure 8 and the Wavestar power matrix in Figure 2 it can be seen that the sea state is above the cut-in of the Wavestar 600kW WEC for large parts of the year.

While both the wind turbine and the WEC operate for a significant part of the year, the majority of this is only at part load. For example, the Wavestar WEC has a capacity factor of around 6%, i.e. on average the WEC generates only 6% of its rated capacity. Furthermore, the generated power fluctuates and there are periods with low wind or wave resource. This is shown exemplary in Figure 9.

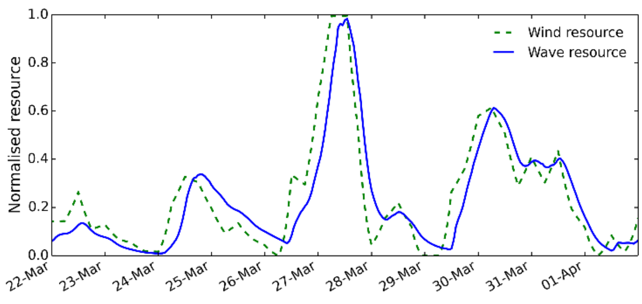

Figure 9: Example of the time delay between the wind and wave energy resource.

It can be seen that both resource profiles follow a similar trend and, more importantly, that the wave resource lags the wind resource by about 5 hours. This lag is due to the slower propagation speed of waves compared to the generating winds.

4.3 Results

The optimisation framework is used to design first a wind only HES and then a HES with wind turbines and WECs. Here the optimisations are performed for the two objectives of minimising the wasted renewable fraction and of maximising the renewable fraction; the latter objectives is equivalent to minimising the fossil fuel generated fraction. These optimisations are repeated for different battery capacities which are expressed in hours of storage for the average electricity demand.

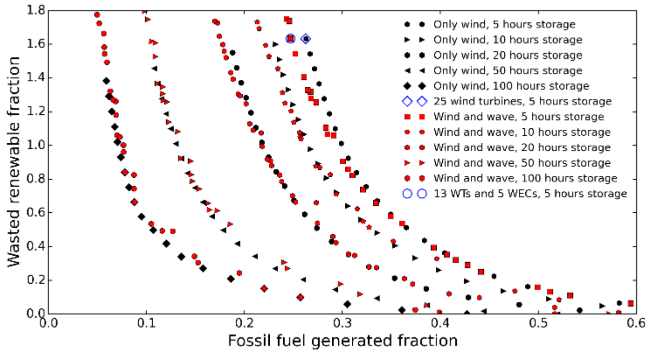

Figure 10: Pareto curves for wind only and wind/wave HES

The results for five different battery capacities from 5 to 100 hours of storage are shown in Figure 10. The points for each battery capacity form a Pareto front and all points on each front are equivalent for the optimisation. For example, the optimisation routine can't decide if a low fossil fuel generated fraction but high wasted renewable fraction is better or worse than a high fossil fuel generated fraction but a low wasted renewable fraction. This point was briefly mentioned in section 2.5 and in Figure 3 but goes beyond this contribution.

It is evident from Figure 10 that the wind only and wind/wave HES show a very similar behaviour and that the only difference occurs at low fossil fuel generated fractions, i.e. high renewable fractions, and low battery capacities. For example, for 5 hours storage a wind only HES achieves a renewable fraction of 73.5% while the wind/wave HES achieves 75% for the same wasted renewable fraction (see blue markers in Figure 10). However, this benefit of the wind/wave HES decreases with increasing battery capacity because for battery capacities above around one day of storage the batteries can effectively smooth the variation in the renewable resource (see Figure 9). For low renewable fractions the diesel generators balance the variations in the renewable resource so that in this case the benefit of the wind/wave HES vanishes.

The increased renewable fraction shows that the time delay between the wind and wave resource can be used to improve the performance of HES. While the improvement in renewable fraction is modest, this was achieved with a WEC designed for more energetic wave climates. By comparing the Wavestar power matrix in Figure 2 with the sea state histogram in Figure 8 it is clear that the WEC almost never reaches its rated output. Thus there is scope for designing WECs for the less energetic seas of the Mediterranean.

5 Conclusion

In this contribution the effect of integrating wave energy converters into wind only HES was investigated. It was shown that wind/wave HES can have an increased renewable fraction for fixed storage capacity. The time delay in the wave resource enables this better utilisation of the renewable resource.

The presented modelling and optimisation framework is based on parameterised models for the devices and hourly resource profiles. The sea state was generated with the state of the art wave numerical model SWAN. While the models are sufficiently detailed to provide an assessment of the HES, a number of simplifications have been made in the battery and diesel generator models. These simplifications have a small effect on the absolute value of the results but have almost no influence on the results relative to each other. Thus these models are adequate for the purpose of this contribution. However, more accurate models will be included in the future to establish accurate costings of the various options. Since the cost of the generated electricity will be the deciding factor, the framework will be used to compare wind only and wind/wave HES once the costs for WECs which are currently in the demonstration phase are established with sufficient accuracy.

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